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The relationship between indoor and outdoor temperature in warm and cool seasons in houses in Brisbane, Australia

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ABSTRACT

The study aimed to identify diurnal indoor temperature patterns and quantify the impact of outdoor on indoor temperature as well as of other modifying factors. Indoor and outdoor temperatures of 77 houses in Brisbane, Australia were monitored with temperature sensors for one year (May 2017–2018). A linear mixed effect model predicted that on average, a 1 °C increase in outdoor temperature resulted in a 0.41 °C increase in indoor temperature during both the cool and warm seasons. The age of the house, building material, roof material and insulation had a moderate influence on indoor temperature. Queenslander houses (a stand-alone timber structure mounted on stumps with an extensive veranda) were, in general, cooler (0.5 °C cooler in winter) and reactive (meaning, having a strong association with the outdoor temperature), while slab-on-ground houses were, in general, warmer (0.3 °C) and stable (meaning, having less association with the outdoor temperature). From the indoor temperature patterns identified for the heated and cooled houses it was concluded that in this climate, heating and cooling is seldom done for 24 h. This quantitative information is crucial for understanding the influence of temperature on human health and household energy consumption at the time when climate change mitigation approaches are being discussed.

1. Introduction

The increase in global temperature and in the frequency of heat waves around the world are of great concern as epidemiological studies have linked exposure to high temperatures with negative effects on human health [1–4]. Low outdoor temperatures also have a significant impact on health, and are an even bigger health risk than high outdoor temperatures in many countries [5–7]. Low and high outdoor temperatures are known causes of cardiovascular and respiratory deaths [5,8,9], while morbidity impacts include increased hospital admissions, workplace accidents, food poisoning, and emergency ambulance dispatches [10–13].

Epidemiological studies use data from networks of outdoor weather stations to estimate personal exposure, since they are readily available whilst indoor temperature data is hard to find. However, exposure risk assessment requires consideration of all the microenvironments where humans spend their time [14]. The lack of indoor temperature data has been attributed to the difficulty of obtaining a sufficient sample size and the use of non-standardised protocols for data collection [15]. The use of outdoor temperature as a surrogate for indoor temperature often leads to significant errors in quantifying temperature exposure risk, because heated or cooled interiors most certainly have very different temperatures to the outdoors. Further, outdoor temperature of only one urban location is often considered, which does not account for human movement between different indoor and outdoor environments, as well as variation in microclimate due to different vegetation cover, urban heat island effect and urban albedo, just to mention a few [16,17]. Moreover, using outdoor temperature does not allow for quantification of the impact of building characteristics on indoor temperature or related morbidity and mortality, as a single external temperature value will mask potential geospatial variations resulting from the heterogeneity of indoor environments.

Studies have related indoor conditions to several meteorological variables, including apparent temperature, relative humidity,

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absolute humidity, maximum temperature, minimum temperature and humidex, as part of the quest to identify the best outdoor parameters that predict the risk of temperature exposure [18,19]. For example, it was found that under warmer temperatures in a temperate climate, indoor temperature correlates strongly with outdoor temperature ($r = 0.91$) while under cooler temperatures the correlation is weaker ($r = 0.41$) [19,20]. In addition to experimental observations, statistical approaches such as multiple regression models have been used to better predict indoor temperature based on outdoor temperature by including environmental factors such as solar radiation [21,22] and dwelling characteristics [23]. However, no ideal parameter that would satisfactorily predict temperature exposure risk in all microenvironments has been identified, partly because most outdoor parameters are highly correlated with one another [24]. Because of this, the actual measurement of the indoor temperature is an important step in order to adequately estimate the risk to human health from exposure to low and high outdoor temperatures.

Measuring indoor temperature is also essential due to its link with energy consumption in the built environment, which accounts for 40% of the global energy consumption. Energy is needed for heating, ventilation and air conditioning (HVAC) of the buildings, as well as lighting to achieve favorable indoor conditions [25].

To address these above research problems, the aims of this study were to:

- Measure indoor and outdoor temperature simultaneously and continuously in a sample of houses for one year;
- Identify the diurnal indoor temperature pattern;
- Determine the association between indoor temperature in households and the immediate surrounding outdoor temperature; and
- Identify factors driving the association (in particular, HVAC system, building characteristics) and the implications for extreme temperature exposure to humans and energy consumption in houses.

Quantification of this association and its modifying factors has not been done before, especially for a subtropical climate.

2. Method

2.1. Climate of the study area

The study was conducted in Brisbane (27° 28′ S, 153° 1′ E), which has a subtropical climate, with mean annual maximum and minimum temperatures of 26.6 °C and 16.6 °C, respectively. Long term mean maximum and minimum temperatures in winter are 21.4 °C and 11.2 °C, respectively. For summers, long term mean maximum and minimum temperatures are 29.3 °C and 21.3 °C, respectively. Also existing records on long term mean relative humidity at summer are 67% (9 am relative humidity) and 59% (3 pm relative humidity). The difference between winter and summer outdoor temperature is smaller than that of most other Australian capital cities because of Brisbane's proximity to the warm ocean current [26,27]. The western and southern suburbs (inland) experience extreme temperatures in both the summer and winter seasons with higher maximums (in summer) and lower minimums (in winter) compared to temperatures in the eastern suburbs, which are influenced by the sea breeze [28,29].

2.2. Housing stock of Brisbane

Pre-1950 houses in Brisbane were dominated by a unique architectural style known as a Queenslander – a vernacular architecture that evolved since the mid-19th century in response to the climate and materials available. The Queenslander is a stand-alone house constructed with single-skin timber walls, corrugated iron roof and suspended timber floors on timber or concrete stumps. Typically these homes have deep eaves or windows awnings, shaded verandas, high ceilings, fully openable (side hinged) doors and windows (timber frame with single glazing), and an internal layout that enables through ventilation. The 'off-ground' nature of this house style provided benefits such as higher air speed for ventilation, pest deterrent (e.g. snakes), flood damage avoidance / mitigation, suitability for construction on non-level ground, and potential for relocation. From the 1950s, brick-veneer houses (i.e. timber framed houses with a brick outer skin and internal lining) were built on concrete slabs. These houses may have corrugated iron or cement tile roofs. Most have aluminium-framed sliding windows (45% opening) with single glazing ([30]; http://www.househistories.org/qld-house-designs-1887-1920). Detached, semi-detached, apartments and the other dwellings constituted 76.4%, 10.0%, 12.6%, and 0.6%, respectively, of the total housing stock of Brisbane [51]. In this study, we differentiate between Queenslanders and Slab-on-Ground (SOG) detached houses. SOG detached house was defined as a single or two-storey dwelling with a concrete slab as a foundation that stands within its grounds and includes private open space (Slab-on-Ground (SOG) houses). Semi-detached house (terrace house or townhouse) was defined as a single or two-storey dwelling that maintains private open space but is attached to other dwellings by a common wall. An apartment (flat) is a dwelling within a group of self-contained dwellings in a building up to three or more storeys in height [31].

2.3. Recruitment of participants

Participants were recruited through email invitation sent via Queensland University of Technology's (QUT's) media office (with a mailing list of about 1000 recipients) and word of mouth within social and family networks. Individuals were eligible if they were 18 years or older and they planned to occupy their house for at least one year. Participation was voluntary and occupants completed consent forms. The study was approved by the QUT Human Research Ethics Committee.

2.4. Housing questionnaire

A questionnaire of 11 questions adapted from He et al. [32] (see A.5) was used to identify factors that, may influence indoor temperature, as well as to gather information on housing characteristics, such as the type of houses, construction material, ventilation practices, use of heating, ventilation and air conditioning (HVAC) and cooking systems. The questionnaire was completed by the occupants with the help of the investigator during the first visit to the house. Houses were termed non-air-conditioned (non-AC) or air-conditioned (AC) dependent on the absence or presence of space heating or cooling devices. It should be noted that the presence of a HVAC system in this climate does not necessarily mean that the system is used with any set frequency. We did not collect data on the actual running times and set point temperatures of such equipment as we expected to be able to identify device operation times from trends in the recorded indoor temperature.

2.5. Indoor and outdoor measurements

The protocol for this study has been described earlier [33]. In summary, indoor and outdoor temperature was measured simultaneously and continuously in the recruited houses using Maxim Integrated DS1921 Hygrochron iButton [50] and Labjack Digit TL Sensors (LabJack Corporation) from May 2017 to May 2018. The sensors recorded air temperature at 30 min intervals. The general specification of both sensors is presented in Tables A.1 and A.2. In

contrast to the previous protocol (where sensors were installed by occupants), in this study sensors were installed by the investigator. Indoor sensors were installed on an inner wall of the living room (out of reach of children; away from sources of heat; and at a location where it would not be moved) and outdoor sensors were placed in a safe location on the south facing wall of the houses to prevent direct solar radiation (Refer to Fig. A.2). After six weeks of measurements, the Maxim Integrated DS1921 Hygrochron iButton sensors were replaced with Labjack Digit TL Sensors at houses that were located more than 30 km away from the Central Business District (CBD) of Brisbane (to reduce travel costs associated with data retrieval due to smaller memory capacity of the original sensors). Houses with the iButtons were visited every six weeks to download data, while data from the Labjack Digit TL Sensors were downloaded every three months.

Although the measurement error is plus/minus 1 ° for an individual reading, the inferences we make concern average changes which use large sample sizes. Hence the influence of the measurement error will be negligible when considering changes in the means estimated using our regression models.

2.6. Data preparation

Raw temperature data were entered into Microsoft Excel 2016 and then read into the R statistical computing software [52], which was used to check for anomalies and missing values, as well as for statistical analyses. Anomalous outdoor temperature data were defined as temperature readings five times greater than, or less than, the same day mean maximum or minimum outdoor temperature as recorded by the Bureau of Meteorology (BOM), Australia. Descriptive statistics for the indoor and outdoor temperature data are in Tables A.4 and A.5.

2.7. Statistical techniques and modeling

A linear mixed-effects model with a random intercept to control for correlated data from individual houses was used, as per Eq. (1), to quantify the relationship between indoor and outdoor temperatures, and to identify differences in indoor temperature due to house characteristics.

$$I_{i,t} \sim \beta_{i,o} + \beta_{i,1} O_{i,t} + \sum \alpha_j X_{i,j} + \varepsilon_{i,t} \quad (1)$$

Where: $I_{i,\ t}$: indoor temperature (°C); ($\beta_{i,\ o}$): random intercept (°C); ($\beta_{i,\ 1}$): random slope; $O_{i,\ t}$: outdoor temperature (°C); α: estimated effect of the building characteristics; $X_{i,\ t}$: building characteristics; and $\varepsilon_{i,\ t}$: error.

The dependent variable $I_{i,t,}$ is the indoor temperature in house i at time t; independent variables were the time-matched outdoor temperature $O_{i,t}$; and matrix of factor variables $X_{i,t}$, which were the building characteristics (see Table A.3). $\varepsilon_{\mathrm{i,t}}$ is the error which was assumed to have a constant variance, and be serially independent and normally distributed. We assumed that the effect of outdoor on indoor temperature would vary by house, therefore we used a random slope ($\beta_{i,1}$). We also assumed that the average indoor temperature would vary by house, therefore a random intercept ($\beta_{i,o}$) was used. These assumptions were based on our prior knowledge that indoor temperature in Brisbane houses on the same day can vary depending on the behaviour of the occupants, and the surroundings of the homes and building materials. We used the model to identify houses where the outdoor temperature had a relatively strong or weak influence on indoor temperature, using a scatter plot of the random intercept and slope estimates.

Table 1
Summary of the characteristics of the 77 houses included in the analysis and number of house with each feature and (percentage out of the total).

Features	N (%)
House type	
SOG[a] (single storey)	28 (36)
SOG[a] (two storey)	21 (27)
Queenslander[b] (single storey)	13 (17)
Queenslander[b] (two storey)	15 (20)
Building material[c]	
Brick veneer	41 (53)
Light weight	32 (42)
Concrete	4 (5)
Roof material	
Metal	40 (52)
Tile	37 (48)
Roof construction	
Pitched	74 (96)
Flat	3 (4)
Roof insulation installed	
Yes	63 (82)
No	14 (18)
Age of house	
1–29 yrs	25 (32)
30–59 yrs	25 (32)
60–100 yrs	25 (32)
Don't Know	2 (3)
Heating system	
Air-conditioned	36 (47)
No heating	41 (53)
Cooling system	
Air-conditioned	59 (77)
No cooling	18 (23)

[a] A single or two-storey detached house with concrete slab as foundation that stands within its own grounds and includes private open space (Slab-on-Ground (SOG) houses).
[b] A single detached house constructed with timber and iron or a timber structure on stumps with an extensive, deep, shaded veranda accessed through French doors (refer to Fig. A.1).
[c] Types of construction of materials of the houses were grouped in concrete, lightweight and brick veneer, where concrete represent house built with mainly concrete. Likewise, lightweight represented houses constructed primarily with timber and brick veneer for brick houses.

3. Results

3.1. The houses

Ninety-four houses were recruited, located in 49 residential suburbs of Brisbane as shown in Fig. 1. The recruited houses included 80 detached houses (51 SOG and 29 Queenslanders), 11 semi-detached and 3 apartments, a distribution that broadly follows the distribution of Brisbane's housing stock. The sample size of the detached houses was sufficiently large for the analysis, and therefore we focused on this group of houses. Four of the houses were excluded from the analysis during the cool season, compared to three houses during the warm season due to lost data and non-cooperation of the participants. The characteristics of the houses are summarized in Table 1**.**

3.2. Outdoor temperature measured by the Bureau of Meteorology

Mean monthly outdoor temperature recorded by the BOM CBD, Brisbane and Archerfield airports weather stations during the period of this study is shown in Fig. A.3. By visual inspection of the BOM data, June to August were selected as representing the cool season and December to February represent the warm season (refer to Fig. A.3).

3.3. Outdoor and indoor temperature of houses

The median annual temperatures were 22.3 °C (IQR: 18.9–25.5 °C) indoors and 24.0 °C (IQR: 21.2–26.4 °C) outdoors.

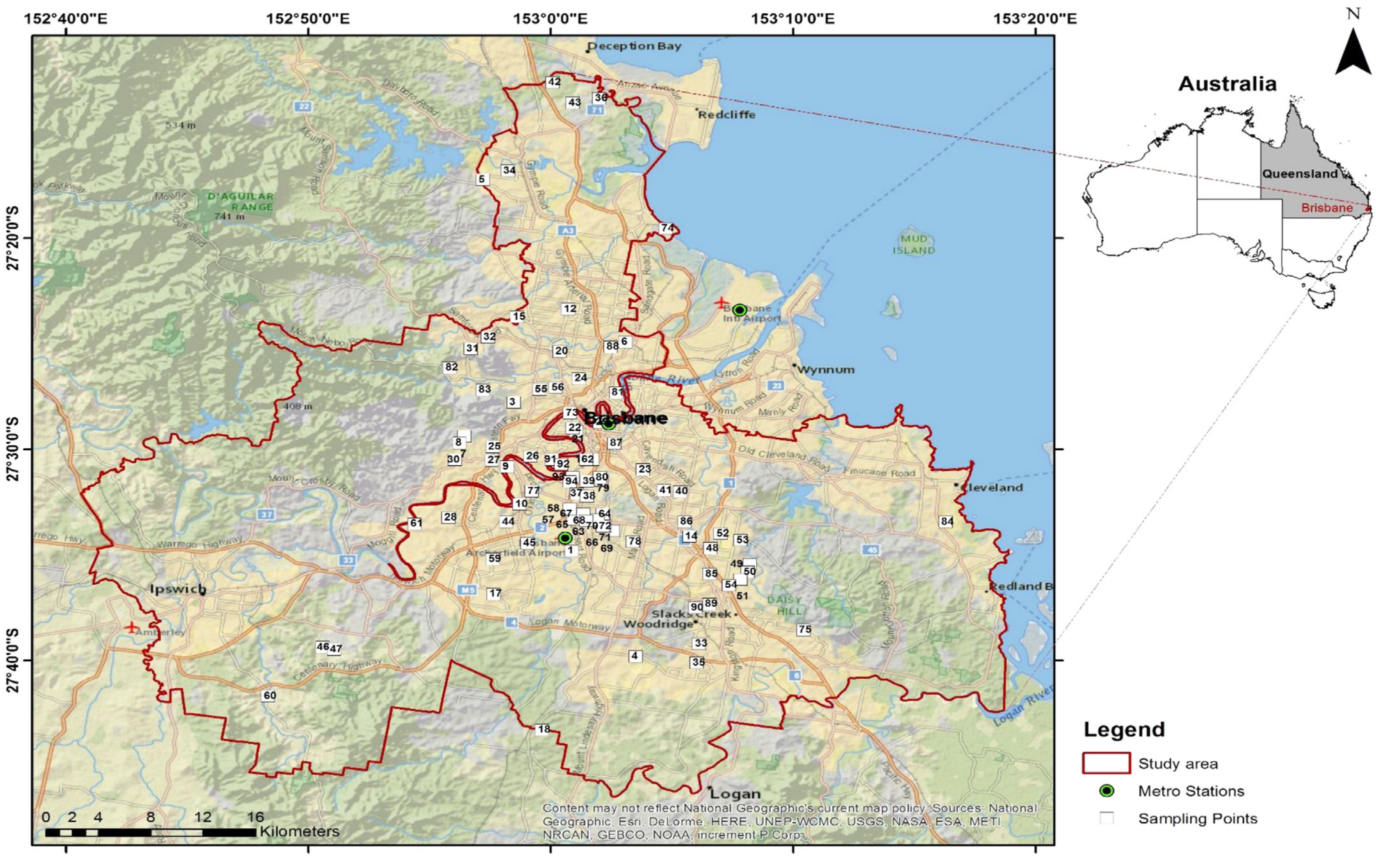

Fig. 1. Map of the study area with the locations of the houses and the three meteorological stations marked.

3.2.1. Cool season

The following analysis relates to the cool season. The median temperatures were 17.0 °C (IQR: 14.0–20.0 °C) indoors and 19.8 °C (IQR: 18.0–21.5 °C) outdoors. The median outdoor temperature was within the range of outdoor temperatures of Brisbane reported by the mentioned BOM stations. Median indoor temperature in about 8% of the houses was between 16 and 18 °C, while in 59% it was between 18 and 20 °C, and in 33%, above 20 °C. Thus, in the majority of the houses (92%) median indoor temperature was within the World Health Organization (WHO) recommended indoor temperature range of 18 to 24 °C as well as the annual 'acceptable' temperature range (18–28 °C) for comfort in this climate. Median indoor temperatures observed in SOG houses (19.9 °C (IQR: 18.0–21.5 °C)) were similar to that of the Queenslanders (19.5 °C (IQR: 17.5–21.5 °C)) and comparable for all types of construction materials (Brick veneer: 20.0 °C (IQR: 18.1–21.5 °C); Concrete: 20.0 °C (IQR: 18.6–21.4 °C); Lightweight: 19.5 °C (IQR: 17.5–21.5 °C)). The lowest median indoor temperature (16.8 °C (IQR: 15.3–17.9 °C)) was recorded in a house located in the western inland suburbs (H18) of Brisbane. This house was a lightweight constructed house and the low thermal mass may have contributed to the low indoor temperature. The highest median indoor temperature (23.3 °C (IQR: 20.5–25.0 °C)) was recorded in a brick veneer house (H29) in a coastal suburb near Moreton Bay.

3.2.2. Warm season

During the warm season, the median indoor and outdoor temperatures were 26.6 °C (IQR: 25.2–28.5 °C) and 25.9 °C (IQR: 23.4–29.0 °C), respectively. In two of the houses the median indoor temperature was between 22.5–25.0 °C while in the majority of the houses (97%) it was between 25.0–28.5 °C. Only in two houses (3%) the median indoor temperature was within the WHO recommended indoor temperature range of 18–24 °C, compared to 92% of the houses during the cool season, but majority was within the annual 'acceptable' temperature range of 18–28 °C for comfort in this climate range. This is consistent with adaptive comfort research. Median indoor temperatures in the houses were comparable between house types (SOG houses: 26.7 °C (IQR: 25.4–28.3 °C); Queenslanders: 26.5 °C (IQR: 25.0–28.5 °C)) and construction materials (Brick veneer: 26.9 °C (IQR: 25.5–28.4 °C); Concrete: 26.2 °C (IQR: 24.6–28.0 °C); Lightweight: 26.5 °C (IQR: 25.0–28.5 °C)). The lowest median indoor temperature (24.5 °C (IQR: 23.4–25.6 °C) in the warm season was recorded in a concrete constructed house (H69) located in coastal suburb, while the highest, in a Queenslander located in an inland suburb (28.5 °C (IQR: 26.5–30.5 °C)).

3.4. Temperature profile over night and day

Time series of mean indoor and outdoor temperatures for all the houses combined (SOG and Queenslander) during the cool and warm seasons are presented in Fig. 2(A) and (B), respectively. Mean indoor temperatures are roughly sinusoidal during both seasons, with both SOG and Queenslander homes showing mean maximum warm season temperatures about 2 ° lower than mean external temperatures. In the cool season, however, SOG homes were able to moderate the minimum indoor temperature. The other difference between the two types of houses was in the time lag between indoor and outdoor temperatures. At the warm peak period of the day, the observed lag time was 1.5 h for SOG houses and 1 h for Queenslander houses. This lag time can be explained by differences in the building envelope, in particular differences in thermal mass. The biggest difference in thermal mass of the houses relates to the construction type and materials used for the floor: the SOG house has a concrete floor that is thermally tied to the ground temperature, whereas the Queenslander has a timber floor and is sus-

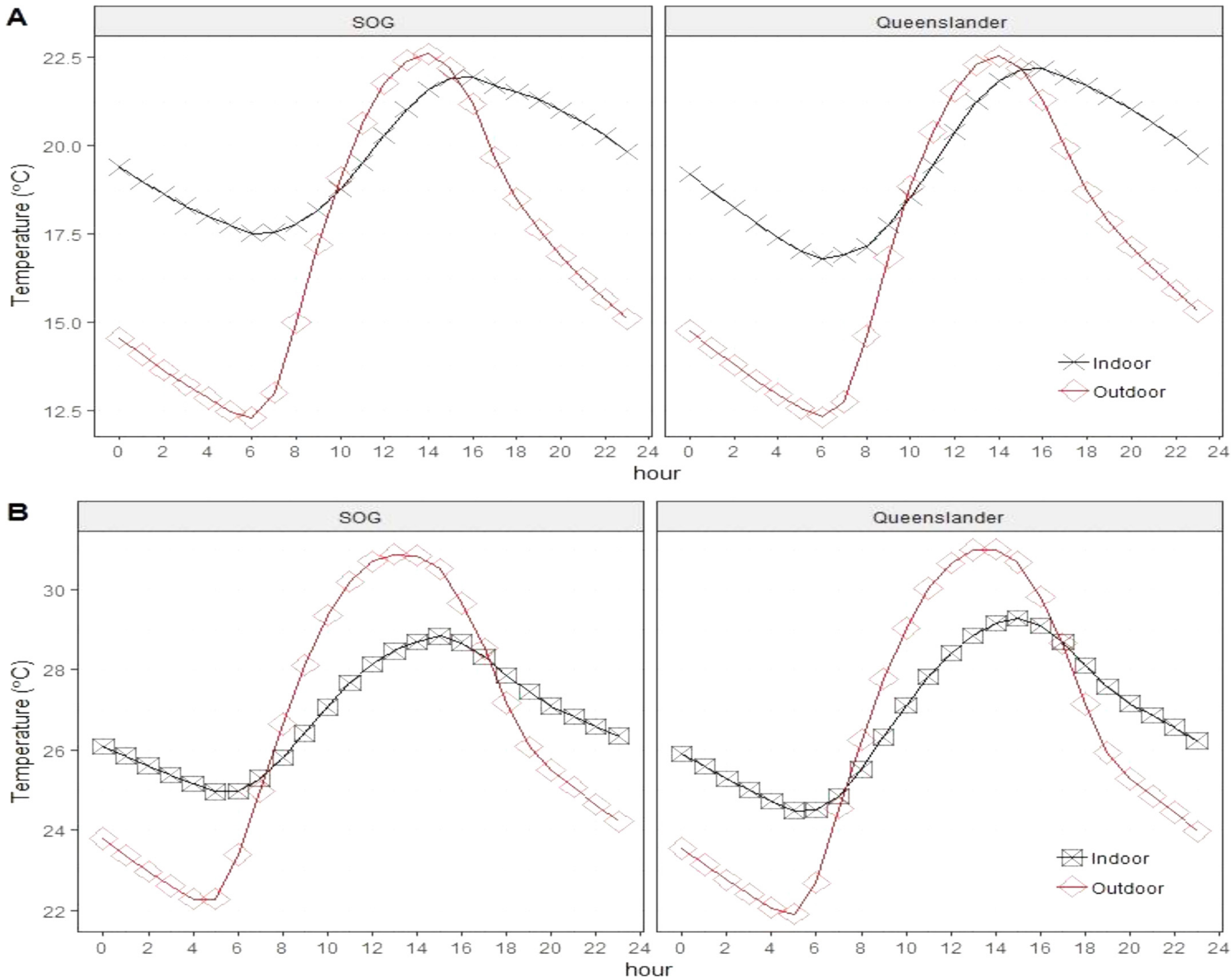

Fig. 2. Hourly mean indoor and outdoor temperatures during the cool (A) and warm (B) seasons in all SOG and Queenslander houses combined.

pended above the ground. Section 2.2 provides a description of the differences between these housing types.

The houses were grouped into AC (heated) and non-AC (non-heated) houses to compare patterns in hourly mean indoor temperature during the cool season (i.e. heating season) as in Fig. 3(A). We could not find a house with hourly mean indoor temperature pattern independent of the corresponding hourly mean outdoor temperature, due to the absence of continuous heating regimes (24 h) in all AC houses. Thus, we selected two houses as examples to illustrate temperature patterns in AC (heated) and non-AC (non-heated) houses. For the AC (heated) house, the hourly mean indoor temperature pattern was closely related to the hourly mean outdoor temperature during most hours of the day, except during the three hour period of 6:00 to 9:00, coinciding with the minimum outdoor temperature. It is presumed that the considerable temperature difference was the result of using a reverse cycle air-conditioner or other heating device, by the occupants.

In contrast, in a non-AC (non-heated) house, the hourly mean indoor temperature pattern closely followed the outdoor temperature pattern, with a small lag, mainly between 10:00 to 14:00.

Regarding the warm season (i.e. cooling season), the houses were group into AC (cooled) and non-AC (not cooled) houses to compare patterns in hourly mean indoor temperature, with examples of one house from each group presented in Fig. 3(B). The hourly mean indoor temperature pattern in AC (cooled) houses was distinctly different from the outdoor temperature pattern due to the use of air-conditioning for cooling purposes: the hourly indoor pattern was nearly flat, with the indoor tempartures lower than the outdoor most of the time, except between 00:00 to 9:00 and 17:00 to 23:00. This indicates that the air conditioner was operating at least between 9:00 and 18:00, with a set point of about 26 °C (+/− 1 °C). It is difficult to determine if it was operating overnight. The overnight indoor temperature profile (higher than the external temperature, but mirroring the rate of temperature decrease) suggests that AC was not operating. This particular temperature profile suggests that natural ventilation was not being used (e.g. windows weren't open to take advantage of cooler overnight temperatures), or that the house had internal thermal mass that slowed down the rate of cooling, or that the building design did not encourage night purging (e.g. hot air trapped against the ceiling, above window height). Conversely the internal temperature profile of the non-AC house very closely aligns with the external temperature profile, suggesting that this house has little thermal mass and very little thermal resistance in the building envelope.

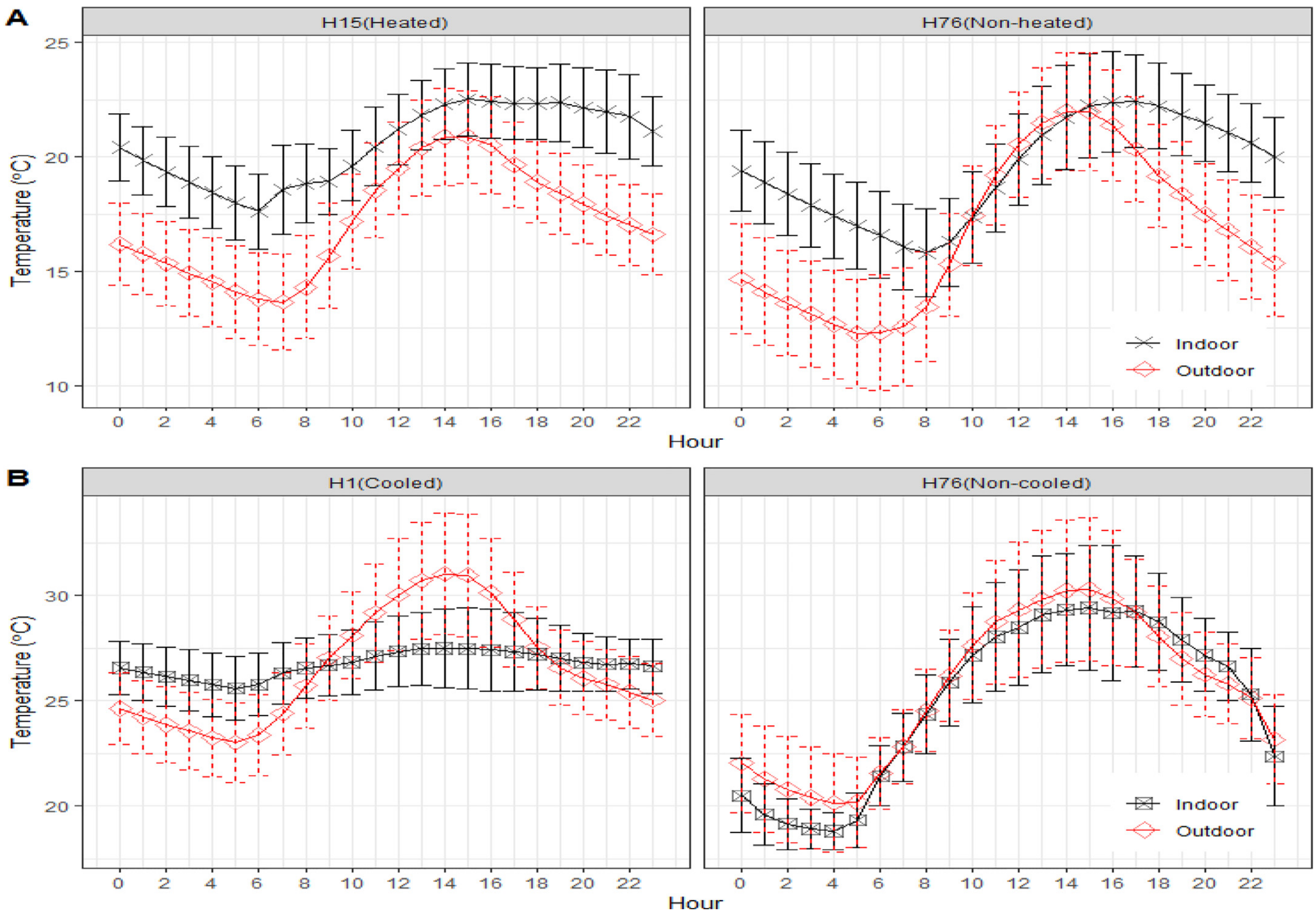

Fig. 3. (A) Daily patterns in hourly mean indoor and outdoor temperatures during cool season in AC (heated) (H15) and non-AC (non-heated) (H76) houses. (B) Daily patterns in hourly mean indoor and outdoor temperatures during the warm season in a cooled (H1) and not cooled (H76) houses. Each panel represents one house.

Table 2
Indoor temperatures (°C) in the cool season as predicted by the mixed effect model (R^2=67%).

Variable (category)	Mean (β)	S.E(β)	95% C.I.	
			lower	upper
Intercept	19.90	0.45	19.02	20.8
Age of house (don't know)	−0.18	0.84	−1.84	1.47
Age of house (30–59 yrs)	−0.07	0.32	−0.70	0.55
Age of house (60–100 yrs)	0.37	0.44	−0.50	1.24
Construction material (concrete)	−0.25	0.58	−1.39	0.89
Construction material (lightweight)	−0.16	0.38	−0.91	0.57
Heat system (no_heat)	−0.11	0.23	−0.57	0.35
House type (Queenslander)	−0.07	0.37	−0.80	0.66
Roof construction (flat)	−0.01	0.63	−1.25	1.23
Roof insulation (yes)	−0.33	0.32	−0.96	0.29
Roof material (tile)	0.01	0.26	−0.51	0.52
Outdoor temperature	0.42	0.02	0.38	0.46

Where Mean (β) is coefficient (estimates) of the independent variables; S.E(β) is standard errors of estimates; 95% C.I. is confidence intervals (CIs) of estimates and R^2 is the coefficient of determination.

Table 3
Indoor temperatures (°C) in the warm season as predicted by the mixed effect model (R^2 = 69%).

Variable (category)	Mean (β)	S.E(β)	95% C.I.	
			lower	upper
Intercept	26.18	0.24	25.72	26.64
Age of house (don't know)	0.15	0.59	−1.02	1.31
Age of house (30–59 yrs)	0.39	0.21	−0.03	0.80
Age of house (60–100 yrs)	0.46	0.30	−0.12	1.04
Construction material (concrete)	−0.10	0.38	−0.85	0.65
Construction material (lightweight)	−0.33	0.24	−0.81	0.15
Cool system (natural ventilation)	0.46	0.22	0.03	0.88
House type (Queenslander)	0.04	0.24	−0.44	0.52
Roof construction (flat)	−0.20	0.42	−1.03	0.63
Roof insulation (yes)	0.16	0.08	0.00	0.33
Roof material (tile)	0.38	0.17	0.04	0.72
Outdoor temperature	0.41	0.02	0.37	0.46

Where Mean (β) is coefficient (estimates) of the independent variables; S.E(β) is standard errors of estimates; 95% C.I. is confidence intervals (CIs) of estimates and R^2 is the coefficient of determination.

3.5. Influence of outdoor temperature and building characteristics on indoor temperature

The estimates of the linear mixed effect model with random intercept (Eq. (1)) are in Tables 2 and 3, including the coefficient (estimates) of the housing characteristics, the mean intercept for outdoor temperature (independent variable); standard errors (SEs), 95% confidence intervals (CIs) and the R^2 (which is the percentage of variance in indoor temperature explained by the independent variables [34]). Our model explained 67% of the variation of indoor temperatures (living room) in the houses during the cool season and 69% in the warm season. These R^2 values were in-line with those of Kelly et al. (45% to 88%), who modelled the indoor temperature in English houses.

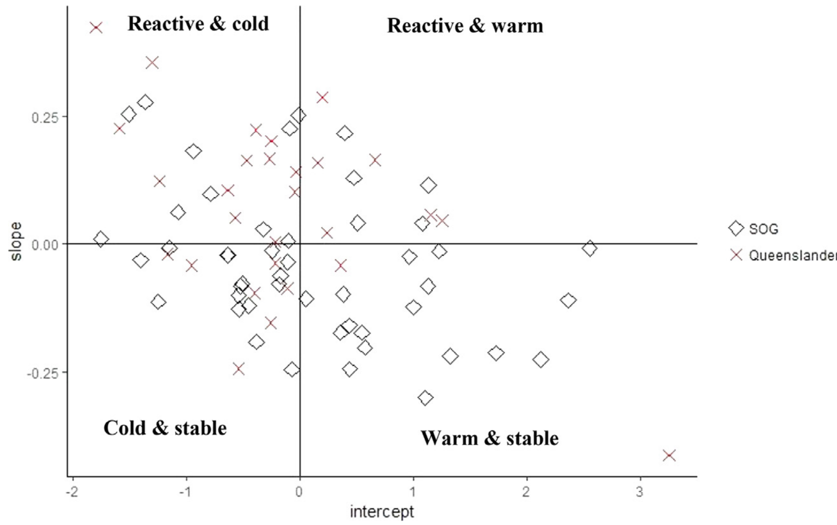

Fig. 4. Scatter plot of differences from the mean slope (0.42) and intercept (20.0 °C) of the regression model (cool season). Houses with a higher than mean intercept are warmer than average. Houses with a higher than mean slope have a stronger association with the outdoor temperature.

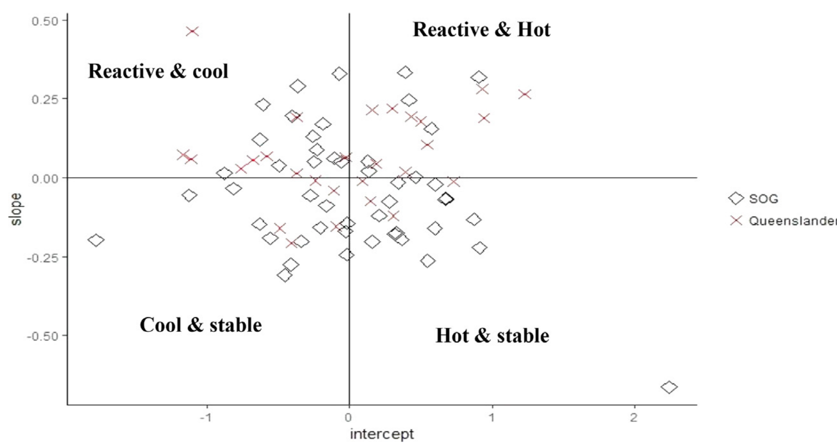

Fig. 5. Scatter plot of differences from the mean slope (0.41) and intercept (26.2 °C) of the regression model (warm season). Houses with a higher than mean intercept are warmer than mean. Houses with a higher than mean slope have a stronger association with the outdoor temperature.

During the cool season, an increase in outdoor temperature of (1 °C) for all the houses was associated with an increase of the indoor temperature of 0.42 °C (95% C.I. = 0.38–0.46). A very similar result was obtained in the warm season, where 1 °C increase in outdoor temperature was associated with an increase of the indoor temperature of 0.41 °C (95% C.I. = 0.37–0.46). The graphical representations of the association during both seasons are shown in Figs. A.6 and A.7.

We used the difference from the mean slope and intercept for houses to identify houses which were warmer than average and had a stronger association with outdoor temperature as presented in Figs. 4 and 5. Houses with higher than mean values of the intercept are warmer/hotter than mean (warm/hot houses). Houses with higher than mean values of the slope have a stronger association with outdoor temperature (reactive houses), while houses with a slope below the mean have a weaker association (stable houses). During the cool season, the Queenslanders were predominantly reactive and cold, while the SOG houses were predominantly warm and stable. The majority of the Queenslander houses were heated while only a few SOG houses were heated. Surprisingly, the warmest and most stable house was a Queenslander (H30) (with roof insulation and heated), as can be seen from the a flat slope and the largest intercept. During the warm season, Queenslander houses were also predominantly reactive /hot, while SOG houses were reactive/stable, cool/hot. None of the Queenslanders were cooled (i.e. no air-conditioning) while all of the SOG houses were cooled (i.e. air-conditioned). The majority of the houses under the considered categories had roof insulation, however the extent of the insulation (i.e. the U_{total} of the roof structure) is not known for any of the houses, and would likely explain some of the variations shown in Figs. A.4 and A.5. It is interesting to note that the differences between the houses is much greater in the cool season than in the warm season and that there are examples of both SOG and Queenslander homes in each quadrant, in each season.

The building characteristics had a moderate impact on the indoor temperature of the houses in both seasons, as shown in Tables 2 and 3. In the cool season, the house age and presence/absence of roof insulation had a moderate impact on indoor temperature. Older houses (65–100 yrs) were 0.37° hotter ($\beta = 0.37$, 95% C.I. = −0.50 to 1.24) on average than the younger. The majority of the older houses were Queenslanders. On average, houses with roof insulation were 0.33° cooler ($\beta = -0.33$, 95% C.I. = −0.96 to 0.29) than those without.

During the warm season, house age, cooling system and construction material (thermal mass) had a fair influence on internal temperatures. In particular, older houses (65–100 yrs) were 0.46° hotter ($\beta = 0.46$, 95% C.I. = −0.12 to 1.04) on average than the

younger. Houses constructed with lightweight materials (timber) were on average 0.33° cooler ($\beta = -0.33$, 95% C.I. = −0.81 to 0.15) than brick veneer houses. As expected, temperatures in houses without any form of cooling were higher, by 0.46° ($\beta = 0.46$, 95% C.I. = 0.03 to 0.88) on average compared to houses with cooling.

4. Discussion and conclusion

In this study, indoor and outdoor (immediate surroundings) temperature of 77 houses were simultaneously measured with temperature sensors (data loggers) for one year. Our data collection technique is comparable to that employed by [35] though in that study outdoor temperature of the immediate surroundings of schools located close to the selected houses was used as a proxy for the outdoor temperature of the houses.

The study provides insights into hourly mean indoor temperature patterns in houses in a subtropical climate, as well as into the relationship between indoor and outdoor temperature and the factors driving the relationship. It offers a quantitative understanding of thermal comfort adjustment behaviours of occupants (house heating or cooling). The general pattern of indoor temperature corresponding to the outdoor temperature in both seasons especially in non-heated and not cooled houses indicated how outdoor temperature and building envelope (insulation, glazing and building material used) impact on indoor temperature as reported by other studies [36,37]. The similarity in outdoor and indoor temperature patterns in the Queenslanders compared to the SOG houses in both seasons (Fig. 2), defines them as reactive to the outdoor temperature. The difference in indoor temperature patterns between the AC (heated) and AC (cooled) houses was attributed to the use of air-conditioning for heating and cooling purposes. From the indoor temperature patterns identified for the AC (heated) and AC (cooled) houses (Figs. 3) it can be concluded that in this climate, heating and cooling is seldom, if ever, operated for 24 h. During the cool season, heating was used in the mornings (7:00 to 9:00) but not at nights when occupants are asleep. In contrast, cooling during the warm season was performed predominantly during sunshine hours (09:00–18:00) and perhaps into the evening (but mostly not overnight). For air conditioned homes, the space heating and cooling demand differs in both duration and time of day. This has a significant implication for the energy consumption of the building stock in the face of global warming and the implications for electricity network planning and operation. Rising mean outdoor temperatures will lead to reduced heating demand in the cool season (an early morning demand that is met by electric or gas heaters) and an increased cooling demand in the warm season (an all-day / late day demand that is all electric) as observed by other research [38]. Evidence of the impact of this was provided in 2017 when, for the first time, the peak demand on the electricity grid for this region was on a hot Sunday afternoon–driven by residential air-conditioning loads [39].

Our findings also provide an insight into occupants' heating and cooling practices, in particular the trigger points at which heating or cooling is activated. The data from this study also suggests that occupants tolerate a broader range of temperatures than those defined by WHO, supporting the body of evidence for the notions of acclimatisation and adaptive comfort [40–42]. Quantitative understanding of heating and cooling behaviours and tolerances would enable more accurate predictions of energy demand for house cooling and heating, as well as development of energy demand models for the entire building stock. With regard to the latter, it is interesting to note that the linear mixed effect modelling indicated that for both the cool and warm seasons, the relationship between indoor and outdoor temperatures in the houses were basically the same of 0.4 °C (after rounding 0.41 °C and 0.42 °C) (Tables 2 and 3). The estimated relationship between indoor and outdoor temperature for the warm season is similar to that reported by [19] in 16 homes of Greater Boston, Massachusetts (humid climate). The scatter plot of differences from the mean slope and intercept of the model for both seasons (Figs. 4 and 5) showed that indoor temperature in most houses had a strong association with outdoor temperature, with a consistent diurnal rise and fall in indoor temperature. Queenslanders were mostly cold (0.5 ° cooler in winter) and reactive (meaning that they had a strong association with the outdoor temperature), while SOG houses were mostly warm (0.3 °) and stable. Hence, the type of the house influences the association between indoor and outdoor temperatures.

The age of houses and roof insulation had a moderate influence on the association between indoor and outdoor temperatures of the houses during the cool season. Higher indoor temperatures recorded in some of the older houses could have been a result of heating by occupants due to the poor thermal efficiency and air leakiness of older houses. Previous studies showed that the presence of insulation in the roof of buildings contributes to less thermal loss and gain [43], making indoor temperature less responsive to outdoor temperature. For the warm season, age of the houses, cooling system, construction material and roof material characteristics of the houses had a modest impact on the association between indoor and outdoor temperature. The hotter indoor temperatures in the older compared to the younger houses depicted that indoor temperature in older houses is strongly correlated to outdoor temperature. Such association in older houses could be due to lack of renovation (energy efficiency regulations did not come into force in Queensland until 2003). The cooler temperatures noted in lightweight constructed houses indicate that the verandas shaded the houses well, limiting heat ingress, and/or benefit from cooling breezes. These lightweight houses were mostly of the Queenslander style, with characteristics as discussed earlier. The influence of cooling systems was demonstrated by the close relationship of internal temperatures of non-cooled houses with the outdoor temperature. The use of heating and cooling appliances by occupants (to achieve preferred indoor temperatures) can mask the effect of building characteristics on the association between indoor and outdoor temperatures, nonetheless the results of this study are consistent with previous studies. The effect of age of house, type of house; ventilation system; and roof insulation on indoor temperature in houses has been noted by other studies [44–47]. This understanding, in particular characterising different housing typologies as reactive or stable, and their propensity to be 'hot' or 'cold' in various seasons, is of critical importance in devising intervention retrofit strategies to improve the resilience of the housing stock (and occupants) to the changing climate.

Our model provided the means to quantify the relationship between indoor and outdoor temperature in houses as well as estimate the influence of building characteristics on it. This study showed that Brisbane residents are exposed to low and high indoor temperatures in cool and warm seasons that could impact on their health, and this was remarkably consistent by housing type. These findings may explain the rise in mortality and hospital admissions in Brisbane when outdoor ambient temperatures are relatively low and high [48,49]. The ability to quantify the relationship between outdoor and indoor temperatures, combined with housing stock characterisation, is of high importance in estimating temperature exposure to humans particularly in residential settings, identifying vulnerable populations and suburbs in the event of extreme weather events (e.g. the rising duration, frequency and intensity of heat waves) and establishing appropriate risk management plans. This study presents a new model to quantify the extent the immediate surrounding outdoor temperature influences indoor temperature in residential settings in Brisbane. The model has an advantage of characterising houses as reactive or stable.

Our study was limited to moderate sample size, but the model is applicable to larger sample sizes and predictions would likely improve with larger data sets. Other limitations of this study included circumstances beyond our control (e.g. loss of participants and sensors) contributed to lost or missing data. During the cool season, the median number of readings per house was 4141, with an interquartile range from 3810 to 4289; whereas the median number of readings during the warm season was 3235 with an interquartile range from 1624 to 3727.

Further research is needed to understand the range of occupant behaviours that impact on indoor temperatures and thermal comfort in the sub-tropics. The evaluation of indoor temperature data via histograms, to determine predominant temperature ranges and durations, is also required, as is the investigation of the indoor/outdoor temperature relationship during weather extremes such as heat waves. Such research, however, requires more robust data collection methods (such as wireless sensors) that would be affordable within the limited research budgets available. Moreover, future studies should include the real energy consumption in houses in the analysis, if available. Finally, the applicability of this approach to temperature analysis needs to be tested against other climates, such as those with a greater differential between warm and cool seasons or greater minimum/ maximum outdoor temperature ranges within seasons.

In conclusion, the relationship between indoor temperature in the houses and the immediate surroundings outdoor temperature was the same (i.e. on average, a 1 °C increase in outdoor temperature resulted in a 0.4 °C increase in indoor temperature during both the cool and warm seasons) and moderately influenced by the age of the houses, building material, roof material and insulation. These findings have implications of temperature exposure to occupants and energy consumption in the houses.

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Declaration of interest

None

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.enbuild.2019.03.010.

Appendices

Table A.1
Specification of DS1921 Hygrochron iButton temperature sensor.

Specification	Details
Enclosure dimensions ($H \times W$)	17 mm × 6 mm
Circuit board dimensions ($H \times W$)	16 mm × 5 mm
Memory	2048 readings
Logging rate	1–255 min
Alarms	Programmable temperature-high and temperature-low alarm-low alarm trip points
Battery life	9.5 Years@ 20 °C and 10 min logging rate
Battery type	3 V lithium
Software	Free
Communication	USB (1-Wire Protocol)
Real-time clock	±2 Min per Month from 0 °C to +45 °C
Memory-Wrap	Yes
Single /Multi-Use	Multi-use
Operating Temperature	−40 °C to +85 °C (−40 °F to +185 °F)
Waterproof Enclosure	Yes
Temperature resolution	0.5 °C
Temperature accuracy	±1 °C

Table A.2
Specification of Labjack Digit-Temperature sensor.

Specification	Details
Enclosure dimensions ($H \times W$)	60 mm × 21 mm
Circuit board dimensions ($L \times W \times H$)	40 mm × 17 mm × 9 mm
Memory	260,000 readings
Logging rate	10 s, 30 s, 1 min, 10 min, 30 min, 1 h, 6h
Alarms	2x user-defined
LED indicators	Green, Red
Battery life	3 Years@ 25 °C and 1 min logging rate
Battery type	3 V lithium, factory replaceable
Software	Free, Windows and Mac
Communication	USB
Real-time clock	±2 s per day
Memory-Wrap	No
Single /Multi-Use	Multi-use
Conformal Coating	Yes
Operating Temperature	−35 °C to +85 °C (−31 °F to +176 °F)
Waterproof Enclosure	Yes, IP68
Temperature resolution	0.067 °C
Temperature accuracy	1 °C

Table A.3
Definition of predictor variables used in the model.

Variable name	Variable type	Category	Reference category
Outdoor temperature (tem_out)	continuous	–	–
Construction material[a]	factor	Light weight (light_wei) Concrete (con) Brick veneer (bri_ve)	Brick veneer
Age of house	factor	Don't know 1–29 yrs 30–59 yrs 60–100 yrs	1–29 yrs
House type	factor	SOG Queenslander	SOG
Heating system[b]	factor	Air-con (ac) No heating (no_heat)	Air-con
Cooling system[c]	factor	Air-con (ac) Natural ventilation (nat_)	Air-con
Roof construction	factor	Pitched Flat	Flat
Roof insulation	factor	Yes No	No
Roof material	factor	Tile Metal	Metal

[a] Types of construction of materials of the houses were grouped in concrete, lightweight and brick veneer, where concrete represent house built with mainly concrete. Likewise, lightweight represented houses constructed primarily with timber and brick veneer for brick houses.
[b] Heating systems were grouped as Air-con (i.e. a combination of heating systems which comprised of Air-con and other form of heating (electric and gas heaters)) and no heating (i.e. houses which used an electric heater or Gas heater only).
[c] Cooling systems were grouped as Air-con (i.e. combination of cooling systems which comprised of Air-con and other form of cooling (portable fan, wall fan)) and natural ventilation (i.e. houses which used of wall fan and portable fan only).

Table A.4
Summary statistics of outdoor and indoor temperature readings obtained at the investigated houses over the cool season (June to August).

House I.D	Type of house	Indoor temperature (°C)					Outdoor temperature (°C)				
		Min.	Median	Max.	Mean (sd)	95% C.I.	Min.	Median	Max.	Mean (sd)	95% C.I.
1.	SOG (two storey)	15.0	21.0	30.5	20.9 (2.1)	20.9, 21.0	9.0	17.0	30.0	17.0 (3.2)	16.9, 17.1
2.	SOG (two storey)	13.5	19.5	28.0	19.3 (2.3)	19.2, 19.4	8.5	17.0	32.0	17.4 (4.3)	17.3, 17.6
3.	SOG (two storey)	12.0	20.0	29.5	20.0 (2.5)	19.9, 20.1	8.5	16.7	28.0	16.8 (3.2)	16.7, 16.9
4.	SOG (two storey)	13.0	20.5	29.2	20.4 (2.6)	20.3, 20.4	6.2	16.5	32.4	17.1 (4.4)	16.1, 17.2
5.	SOG (single storey)	13.0	20.8	31.1	20.7 (3.0)	20.6, 20.8	9.5	18.1	32.7	18.7 (4.0)	18.6, 18.9
6.	SOG (single storey)	15.5	20.5	26.5	20.3 (1.5)	20.2, 20.3	6.5	16.5	32.0	16.9 (4.4)	16.7, 17.0
7.	SOG (single storey)	12.5	19.3	2.5	19.2 (2.6)	19.1, 19.3	6.5	17.0	32.0	17.5 (4.9)	17.3, 17.6
8.	SOG (single storey)	15.0	20.0	25.5	19.8 (1.8)	19.3, 20.3	4.5	15.5	29.5	15.4 (4.5)	15.2, 15.5
9.	SOG (two storey)	14.0	19.5	30.0	19.8 (2.5)	19.7, 19.8	8.0	17.0	31.5	17.2 (3.9)	17.0, 17.3
10.	SOG (single storey)	17.0	20.0	24.5	20.1 (2.1)	19.9, 20.4	8.0	16.0	26.0	16.6 (4.7)	16.0, 17.1
11.	Queenslander (two storey)	13.5	18.0	29.0	18.4 (2.3)	18.3, 18.5	10.0	17.0	31.0	17.3 (3.3)	17.2, 17.5
12.	SOG (single storey)	15.0	20.0	27.5	20.0 (2.4)	19.9, 20.2	9.5	17.5	31.0	18.0 (4.4)	17.8, 18.2
13.	SOG (single storey)	11.5	18.5	27.0	18.6 (2.5)	18.5, 18.7	6.0	16.0	31.1	16.2 (4.1)	16.0, 16.3
14.	SOG (single storey)	15.6	19.8	27.0	20.1 (2.2)	19.9, 20.2	7.4	17.3	31.1	17.8 (4.9)	17.5, 18.1
15.	Queenslander (two storey)	14.0	20.5	30.0	20.6 (2.3)	20.5, 20.6	9.5	17.0	30.0	17.2 (3.0)	17.1, 17.3
16.	Queenslander (two storey)	13.0	19.0	27.50	19.2 (3.3)	18.8, 19.6	8.0	16.7	28.0	16.7 (4.9)	16.1, 17.2
17.	Queenslander (single storey)	10.0	18.4	29.5	18.5 (3.2)	18.3, 18.6	6.5	16.5	33.0	17.1 (5.3)	16.9, 17.2
18.	SOG (two storey)	11.6	16.8	26.1	16.7 (2.0)	16.7, 16.8	6.3	15.5	28.5	15.5 (3.6)	15.4, 15.6
19.	SOG (two storey)	14.9	19.4	25.1	19.4 (1.5)	19.4, 19.5	6.4	16.3	32.0	16.4 (4.4)	16.3, 16.5
20.	SOG (single storey)	12.5	20.0	30.0	20.0 (2.8)	19.8, 20.0	7.0	16.5	31.5	16.8 (4.3)	16.6, 16.9
21.	SOG (single storey)	14.0	18.5	28.0	18.9 (2.2)	18.8, 18.9	6.5	16.0	32.0	16.4 (4.7)	16.3, 16.2
22.	Queenslander (single storey)	13.0	19.5	28.5	19.4 (2.6)	19.2, 19.6	9.5	17.5	28.5	17.9 (3.9)	17.6, 18.2
23.	SOG (two storey)	13.5	20.8	30.0	20.7 (2.9)	20.5, 20.9	6.4	16.8	31.1	17.0 (5.2)	16.6, 17.3
24.	SOG (single storey)	15.5	19.5	25.3	19.6 (1.9)	19.5, 19.7	6.0	16.7	31.6	16.6 (4.3)	16.4, 16.7
25.	Queenslander (single storey)	13.5	20.7	30.0	20.7 (3.0)	20.6, 20.9	6.3	16.4	31.1	16.8 (5.2)	16.5, 17.1
26.	Queenslander (two storey)	13.5	19.5	29.8	19.5 (2.9)	19.4, 19.6	5.0	16.5	32.2	16.5 (5.2)	16.3, 16.6
27.	SOG (two storey)	10.5	18.3	30.0	18.3 (3.3)	18.2, 18.4	7.5	16.9	31.5	16.9 (3.9)	16.7, 17.0
28.	SOG (single storey)	10.0	17.8	27.0	17.8 (2.9)	17.7, 17.9	6.5	16.7	33.4	16.7 (4.9)	16.6, 16.9
29.	SOG (single storey)	11.3	23.3	28.5	22.6 (3.2)	22.5, 22.7	6.9	18.0	33.4	18.0 (4.3)	17.9, 18.2
30.	Queenslander (single storey)	20.0	23.0	26.0	23.1 (1.5)	23.0, 23.2	7.0	16.6	27.5	16.7 (4.6)	16.3, 17.0
31.	Queenslander (two storey)	15.5	20.5	25.5	20.3 (2.3)	20.1, 20.5	9.0	17.8	27.5	17.8 (4.2)	17.4, 18.1
32.	Queenslander (two storey)	12.0	19.5	29.5	19.3 (2.6)	19.3, 19.4	8.0	17.0	31.0	17.1 (3.4)	16.9, 17.2
33.	SOG (single storey)	16.8	20.3	28.5	20.3 (1.6)	20.2, 20.3	3.1	15.6	36.5	15.8 (5.6)	15.7, 16.0
34.	SOG (single storey)	17.5	21.5	31.8	21.8 (1.89)	21.7, 21.8	7.5	18.0	37.1	18.8 (5.2)	18.6, 18.9

(*continued on next page*)

Table A.4 (*continued*)

House I.D	Type of house	Indoor temperature (°C)					Outdoor temperature (°C)				
		Min.	Median	Max.	Mean (sd)	95% C.I.	Min.	Median	Max.	Mean (sd)	95% C.I.
35.	SOG (single storey)	13.0	20.0	28.5	19.8 (2.0)	19.7, 19.8	9.0	18.0	32.0	18.0 (4.0)	17.9, 18.1
36.	SOG (single storey)	14.0	19.6	28.0	19.6 (1.9)	19.5, 19.7	4.5	16.4	32.5	16.4 (5.0)	16.2, 16.7
37.	SOG (single storey)	18.0	21.8	27.5	21.8 (1.6)	21.8, 21.9	5.5	16.2	31.6	16.2 (4.7)	16.1, 16.4
38.	SOG (single storey)	14.5	21.2	28.7	21.2 (2.2)	21.1, 21.3	6.0	17.0	31.4	17.1 (4.4)	17.0, 17.3
39.	Queenslander (single storey)	10.0	19.0	31.0	19.2 (3.6)	19.0, 19.3	5.0	15.5	31.0	15.7 (4.5)	15.5, 15.8
40.	SOG(two storey)	13.0	19.0	27.0	19.1 (2.3)	19.0, 19.2	6.0	16.5	31.5	16.9 (4.3)	16.7, 17.0
41.	SOG (two storey)	14.5	19.5	27.0	19.2 (1.8)	19.2, 19.3	8.0	17.5	31.5	17.6 (4.1)	17.4, 17.7
42.	SOG (single storey)	15.5	19.5	23.0	19.2 (1.4)	19.1, 19.2	8.0	16.5	31.0	16.9 (3.9)	16.8, 17.1
43.	SOG (two storey)	14.0	17.5	24.5	17.7 (1.7)	17.7, 17.8	9.5	17.5	29.0	16.5 (3.2)	16.4, 16.7
44.	Queenslander (single storey)	12.0	19.5	28.5	19.5 (2.6)	19.4, 19.6	6.0	15.5	31.5	16.4 (4.7)	16.2, 16.6
45.	Queenslander (single storey)	13.1	19.4	30.3	19.4 (3.0)	19.3, 19.6	10.5	17.9	28.6	17.9 (3.3)	17.7, 18.1
46.	SOG (single storey)	14.5	20.5	30.0	20.5(2.3)	20.4, 20.6	9.5	18.0	31.5	18.3 (3.7)	18.2, 18.4
47.	Queenslander (two storey)	13.0	20.0	29.5	19.8 (3.4)	19.5, 20.0	11.5	18.5	30.5	18.8 (3.3)	18.5, 19.0
48.	SOG (single storey)	12.9	19.1	31.8	19.0 (2.5)	18.9, 19.1	4.2	15.4	31.8	15.9 (5.6)	15.7, 16.1
49.	SOG (two storey)	14.0	20.5	27.0	20.2 (1.34)	20.2, 20.3	7.0	16.7	32.0	16.7 (4.5)	16.6, 16.9
50.	SOG (single storey)	11.9	18.8	29.3	18.8 (3.0)	18.7, 18.9	7.1	16.2	31.8	16.4 (4.1)	16.3, 16.5
51.	Queenslander (two storey)	10.5	19.0	28.5	19.1 (3.2)	18.9, 19.2	7.0	16.5	30.5	16.5 (4.1)	16.3, 16.6
52.	Queenslander (two storey)	13.0	19.5	29.0	19.7 (2.2)	19.7, 19.8	7.5	17.1	33.0	17.1 (4.5)	16.9, 17.2
53.	Queenslander (single storey)	13.5	19.5	25.5	19.3 (2.4)	19.2, 19.5	9.0	18.0	31.0	18.1 (4.2)	17.9, 18.4
54.	Queenslander (two storey)	9.5	19.5	31.0	19.2 (3.9)	18.9, 19.4	7.0	18.5	33.0	18.7 (5.4)	18.3, 19.0
55.	SOG (single storey)	15.0	19.5	23.5	19.1 (2.0)	18.9, 19.2	8.5	17.5	25.5	17.3 (4.0)	17.0, 17.6
56.	SOG (two storey)	12.0	19.0	24.0	18.5 (2.6)	18.2, 18.7	5.5	16.5	26.5	16.3 (5.1)	15.9, 16.7
57.	Queenslander (single store)	11.5	19.5	25.0	19.2 (3.1)	19.0, 19.5	7.0	16.8	26.5	16.7 (4.9)	16.3, 17.1
58.	SOG (two storey)	14.0	21.0	27.0	20.5 (2.9)	20.3, 20.7	7.5	17.5	25.0	16.8 (4.0)	16.5, 17.2
59.	Queenslander (single storey)	11.5	19.0	25.0	18.6 (2.9)	18.4, 18.9	4.0	17.0	31.0	17.2 (6.5)	16.7, 17.7
60.	Queenslander (two storey)	14.5	19.5	23.6	19.2 (1.6)	19.2, 19.3	7.5	16.7	26.8	16.7 (3.7)	16.6, 16.9
61.	Queenslander (two storey)	11.5	19.5	28.0	19.3 (2.8)	19.2, 19.4	8.0	17.0	31.0	17.2 (4.0)	17.1, 17.4
62.	Queenslander (single storey)	13.5	20.0	29.0	19.9 (2.5)	19.8, 20.0	8.5	17.0	30.5	17.1 (3.9)	16.9, 17.1
63.	SOG (two storey)	16.0	20.5	29.0	20.5 (1.5)	20.4, 20.5	9.5	17.0	29.0	17.0 (3.1)	16.7, 17.1
64.	SOG (two storey)	11.0	18.0	26.5	17.9 (2.4)	17.8, 18.0	8.0	16.5	29.5	16.6 (3.4)	16.3, 16.6
65.	Queenslander (two storey)	13.0	20.0	29.0	19.9 (2.9)	19.7, 20.1	8.0	17.0	31.5	17.6 (4.7)	17.2, 17.9
66.	Queenslander (two storey)	16.5	21.0	29.0	20.8 (1.8)	20.7, 20.9	13.5	18.5	28.5	18.8 (2.3)	18.7, 18.9
67.	SOG (two storey)	13.1	18.0	26.1	18.0 (2.0)	17.9, 18.0	3.6	14.6	30.3	14.6 (4.9)	14.5, 14.7
68.	SOG (single storey)	8.9	19.0	31.8	19.0 (3.2)	18.9, 20.0	8.5	18.0	28.3	17.7 (2.6)	17.6, 17.8
69.	SOG (single storey)	15.5	20.5	26.9	20.5 (2.2)	20.4, 20.6	9.8	18.5	35.3	19.2 (4.7)	19.0, 19.3
70.	Queenslander (two storey)	12.0	20.5	30.0	20.3 (2.3)	20.3, 20.4	8.0	16.5	30.5	16.7 (3.6)	16.6, 16.8
71.	SOG (two storey)	14.5	20.5	30.5	20.3 (2.5)	20.2, 20.4	10.5	18.0	30.5	18.0 (3.3)	17.8, 18.1
72.	SOG (two storey)	18.5	22.0	28.5	21.9 (1.4)	21.9, 22.0	9.5	17.0	29.5	17.2 (3.1)	17.1, 17.3
73.	Queenslander (single storey)	13.6	19.7	29.8	19.7 (3.1)	19.5, 20.0	7.9	17.1	30.7	17.3 (4.4)	17.0, 17.6
74.	SOG (two storey)	16.5	20.0	27.5	19.9 (1.5)	19.8, 19.9	8.0	17.5	32.5	18.0 (4.0)	17.8, 18.1
75.	SOG (single storey)	12.5	19.5	30.5	19.4 (2.8)	19.4, 19.6	9.5	18.5	30.5	18.5 (3.4)	18.4, 18.6
76.	Queenslander (single storey)	12.0	19.5	31.0	19.5 (2.9)	19.4, 19.5	7.5	16.8	31.0	16.8 (4.1)	16.6, 16.9

Table A.5
Summary statistics of outdoor and indoor temperature readings obtained at the investigated houses over the warm season (December to February).

House I.D	Type of house	Indoor temperature (°C)					Outdoor temperature (°C)				
		Min.	Median	Max.	Mean (sd)	95% C.I.	Min.	Median	Max.	Mean (sd)	95% C.I.
1.	SOG (two storey)	20.0	26.5	32.0	26.7 (1.6)	26.7, 26.8	19.0	26.5	36.5	26.6 (3.4)	26.5, 26.7
2.	SOG (two storey)	20.5	27.5	35.0	27.4 (2.5)	27.3, 27.4	17.0	26.0	36.5	26.8 (4.6)	26.6, 27.0
3.	SOG (two storey)	19.5	26.0	34.0	26.3 (2.7)	26.2, 26.4	18.0	25.0	36.5	25.7 (3.4)	25.5, 25.8
4.	SOG (two storey)	21.40	26.3	30.9	26.2 (1.4)	26.2, 26.2	17.1	25.4	36.9	26.3 (4.7)	26.2, 26.5
5.	SOG (single storey)	20.4	25.4	31.6	25.5 (2.0)	25.4, 25.6	19.4	25.9	36.9	26.9 (4.1)	26.8, 27.1
6.	SOG (single storey)	22.5	26.0	30.5	26.2 (1.1)	26.1, 26.2	16.0	25.0	36.5	25.8 (4.8)	25.6, 25.9
7.	SOG (single storey)	21.0	27.0	34.5	27.0 (2.4)	26.9, 27.0	17.0	26.0	36.5	26.3 (4.2)	26.1, 26.4
8.	SOG (single storey)	21.5	26.5	33.0	26.9 (1.9)	26.8, 26.9	16.0	24.5	36.5	25.0 (3.9)	24.8, 24.1
9.	SOG (two storey)	20.5	27.0	32.5	26.8 (1.9)	26.7, 26.8	17.0	23.5	36.5	26.2 (3.8)	26.1, 26.3
10.	SOG (single storey)	22.0	28.0	34.0	27.8 (2.3)	27.7, 27.9	18.0	26.5	36.5	27.1 (4.3)	27.0, 27.3
11.	Queenslander (two storey)	20.0	25.5	34.0	25.5 (2.1)	25.4, 25.5	19.0	26.0	36.5	26.1 (3.4)	26.0, 26.2
12.	SOG (single storey)	22.0	26.5	31.50	26.3 (1.7)	26.2, 26.3	18.5	26.0	36.5	26.5 (4.2)	26.4, 26.7
13.	SOG (single storey)	21.1	25.2	34.7	25.7 (2.8)	25.6, 25.7	16.2	25.3	36.9	26.1 (4.8)	25.9, 26.2
14.	SOG (single storey)	21.6	26.8	33.5	27.0 (2.1)	26.9, 27.0	18.0	26.0	36.9	26.5 (4.2)	26.4, 26.6
15.	Queenslander (two storey)	20.0	26.5	33.0	26.6 (2.1)	26.5, 26.6	18.0	25.5	36.5	25.9 (3.4)	25.8, 26.0
16.	Queenslander (two storey)	19.0	27.0	36.0	27.2 (3.0)	27.1, 27.2	17.0	26.0	36.5	26.7 (4.3)	26.5, 26.8
17.	Queenslander (single storey)	19.0	27.5	37.0	27.8 (3.3)	27.7, 27.9	16.0	25.5	36.5	26.0 (4.6)	25.8, 26.1
18.	SOG (two storey)	19.4	25.6	32.2	25.7 (2.1)	25.6, 25.7	16.6	24.3	36.6	24.7 (3.4)	24.5, 24.8
19.	SOG (two storey)	21.6	26.3	30.7	26.3 (1.8)	26.3, 26.4	17.6	26.0	36.9	26.7 (4.3)	26.5, 26.8
20.	SOG (single storey)	20.5	27.5	35.5	27.6 (2.5)	27.4, 27.6	17.5	26.5	36.5	26.8 (4.4)	26.7, 26.9
21.	SOG (single storey)	22.5	27.5	34.0	27.6 (2.0)	27.5, 27.6	17.5	26.0	36.5	26.7 (4.0)	26.5, 26.8
22.	Queenslander (single storey)	19.0	27.0	34.0	26.8 (2.4)	26.7, 26.9	18.5	26.5	36.5	27.1 (4.2)	27.0, 27.2

(*continued on next page*)

Table A.5 (*continued*)

House I.D	Type of house	Indoor temperature (°C)					Outdoor temperature (°C)				
		Min.	Median	Max.	Mean (sd)	95% C.I.	Min.	Median	Max.	Mean (sd)	95% C.I.
23.	SOG (two storey)	20.7	27.3	34.8	27.2 (2.2)	27.1, 27.3	19.0	25.8	35.4	25.9 (2.7)	25.9, 26.0
24.	SOG (single storey)	21.7	26.4	31.3	26.3 (1.7)	26.3, 26.4	16.8	25.2	36.9	25.9 (4.2)	25.7, 26.0
25.	Queenslander (single storey)	20.4	27.1	35.6	27.1 (2.5)	27.0, 27.2	16.0	25.9	36.9	25.9 (4.1)	25.8, 26.0
26.	Queenslander (two storey)	20.8	26.3	32.0	26.4 (2.1)	26.3, 26.4	16.6	25.3	36.9	26.1 (4.6)	26.0, 26.2
27.	SOG (two storey)	18.6	26.9	36.6	27.0 (3.5)	26.9, 27.1	16.9	25.3	36.9	26.0 (4.2)	25.9, 26.1
28.	SOG (single storey)	19.7	26.2	33.3	26.1 (2.2)	26.1, 26.2	17.4	25.2	36.9	26.2 (4.7)	26.1, 26.4
29.	SOG (single storey)	21.2	27.1	32.2	27.2 (1.8)	27.2, 27.3	18.2	26.4	36.9	27.2 (4.5)	27.1, 27.3
30.	Queenslander (single storey)	20.5	26.0	31.5	25.9 (1.8)	25.9, 26.0	17.0	25..0	36.5	25.8 (4.6)	25.7, 26.0
31.	Queenslander (two storey)	21.0	28.0	35.0	27.9 (2.3)	27.8, 28.0	17.5	26.0	36.5	26.5 (4.3)	26.3, 26.6
32.	Queenslander (two storey)	20.0	27.5	36.0	27.1 (2.7)	27.1, 27.3	18.0	25.0	35.5	25.2 (3.1)	25.1, 25.3
33.	SOG (single storey)	24.2	27.5	30.8	27.3 (1.4)	27.1, 27.5	19.9	26.2	36.9	27.3 (4.7)	26.7, 28.0
34.	SOG (single storey)	22.4	26.8	32.7	27.1 (1.8)	27.0, 27.1	17.4	25.9	36.9	26.9 (4.7)	26.7, 27.1
35.	SOG (single storey)	21.5	27.0	33.5	27.2 (2.2)	27.1, 27.2	18.5	27.0	36.5	27.2 (3.8)	27.1, 27.4
36.	SOG (single storey)	22.0	27.0	35.5	27.4 (2.1)	27.3, 27.4	16.5	25.0	36.5	26.0 (4.6)	25.9, 26.1
37.	SOG (single storey)	24.0	27.7	33.4	27.8 (1.6)	27.7, 27.9	17.6	26.6	36.9	27.2 (4.6)	27.1, 27.4
38.	SOG (single storey)	21.5	28.1	35.3	28.2 (2.8)	28.2, 28.4	17.7	26.0	36.9	26.6 (4.3)	26.4, 26.7
39.	Queenslander (single storey)	19.0	25.5	36.5	26.0 (2.7)	25.9, 26.1	16.5	25.5	36.5	26.0 (4.3)	25.8, 26.1
40.	SOG(two storey)	18.0	27.5	36.0	26.9 (3.0)	26.8, 27.0	17.5	25.5	26.0	26.0 (4.0)	25.9, 26.1
41.	SOG (two storey)	22.0	27.0	32.5	27.0 (1.8)	26.9, 27.0	18.5	26.5	36.5	26.6 (3.8)	26.5, 26.7
42.	SOG (single storey)	18.0	26.4	32.9	26.5 (2.1)	26.3, 26.6	17.9	25.5	36.9	26.5 (4.5)	26.3, 26.6
43.	SOG (two storey)	21.5	26.5	32.5	26.5 (1.8)	26.2, 26.6	18.0	25.0	34.5	25.1 (2.8)	25.0, 25.2
44.	Queenslander (single storey)	20.0	26.0	34.0	26.3 (2.1)	26.3, 26.4	16.5	24.5	36.5	25.0 (4.2)	24.8, 25.1
45.	Queenslander (single storey)	19.8	26.6	35.5	26.6 (2.4)	26.5, 26.7	18.5	25.6	36.5	25.6 (3.2)	25.8, 26.0
46.	SOG (single storey)	18.5	27.5	36.5	27.4 (3.4)	27.3, 27.5	18.5	26.5	36.5	26.5 (4.0)	26.9, 27.2
47.	Queenslander (two storey)	20.5	27.5	35.5	27.7 (2.7)	27.6, 27.8	18.5	26.5	36.5	26.6 (3.6)	26.5, 26.7
48.	SOG (single storey)	21.1	27.3	32.2	27.3 (1.8)	27.2, 27.3	16.8	25.6	36.9	26.2 (4.3)	26.1, 26.3
49.	SOG (two storey)	21.5	27.5	32.0	27.3 (1.8)	27.2, 27.3	17.0	25.0	36.5	26.1 (4.5)	25.9, 26.2
50.	SOG (single storey)	20.1	27.1	37.1	27.6 (3.5)	27.5, 27.7	17.2	25.6	36.9	26.2 (4.2)	26.1, 26.3
51.	Queenslander (two storey)	18.5	27.5	33.5	27.2 (2.2)	27.2, 27.3	17.0	25.5	36.5	26.0 (4.0)	25.9, 26.1
52.	Queenslander (two storey)	20.5	26.5	32.5	26.5 (1.7)	26.4, 26.5	17.5	26.0	36.5	26.4 (4.3)	26.2, 26.5
53.	Queenslander (single storey)	20.5	27.0	33.5	26.9 (2.4)	26.8, 27.0	17.5	26.0	36.5	26.4 (3.9)	26.2, 26.5
54.	Queenslander (two storey)	18.5	26.5	35.5	26.9 (2.9)	26.8, 27.0	17.0	26.0	36.5	26.6 (4.4)	26.4, 26.7
55.	SOG (single storey)	20.0	26.5	33.0	26.5 (2.4)	26.4, 26.5	18.0	26.0	36.5	26.6 (3.9)	26.5, 26.7
56.	SOG (two storey)	20.0	27.5	33.5	27.2 (2.1)	27.1, 27.2	16.5	26.0	36.5	26.8 (4.8)	26.6, 26.9
57.	Queenslander (single store)	18.5	26.5	35.0	26.5 (2.9)	26.4, 26.6	17.0	26.0	36.5	26.5 (4.4)	26.3, 26.6
58.	SOG (two storey)	18.0	26.5	37.5	26.8 (3.4)	26.7, 26.9	18.5	26.5	36.5	26.7 (3.4)	26.6, 26.8
59.	Queenslander (single storey)	20.5	27.5	35.0	27.5 (2.5)	27.4, 27.6	16.5	27.0	36.5	27.7 (4.8)	27.5, 27.8
60.	Queenslander (two storey)	21.3	26.3	31.9	26.3 (1.8)	26.2, 26.3	17.4	25.8	36.8	26.0 (3.4)	25.9, 26.1
61.	Queenslander (two storey)	20.0	26.5	34.5	26.8 (2.5)	26.7, 26.8	18.0	26.5	36.5	27.1 (4.5)	27.0, 27.2
62.	Queenslander (single storey)	20.0	26.0	35.0	26.0 (2.1)	25.9, 26.0	18.0	26.0	36.5	25.4 (3.7)	26.3, 26.5
63.	SOG (two storey)	22.0	27.0	34.0	27.1 (1.7)	27.1, 27.2	20.5	27.0	36.5	27.0 (2.7)	26.9, 27.1
64.	SOG (two storey)	19.5	25.5	31.0	25.2 (2.0)	25.2, 25.3	17.5	25.0	35.0	25.0 (3.3)	24.9, 25.1
65.	Queenslander (two storey)	19.0	26.0	35.0	26.3 (2.5)	26.2, 26.3	17.0	25.0	36.5	26.1 (4.6)	25.9, 26.2
66.	Queenslander (two storey)	21.5	27.5	33.5	27.5 (2.1)	27.4, 27.5	20.0	26.0	34.5	26.1 (2.5)	26.0, 26.1
67.	SOG (two storey)	21.6	27.1	32.6	27.1 (2.0)	27.0, 27.1	14.30	24.5	36.9	25.2 (4.8)	25.1, 25.4
68.	SOG (single storey)	19.9	26.4	34.1	26.6 (2.4)	26.5, 26.6	17.6	25.8	36.9	26.1 (3.7)	26.0, 26.2
69.	SOG (single storey)	20.2	24.5	30.6	24.6 (1.7)	24.6, 24.7	18.6	25.9	36.9	27.0 (4.5)	27.0, 27.2
70.	Queenslander (two storey)	20.0	28.5	37.0	28.6 (3.0)	28.5, 28.6	18.0	25.5	36.5	26.1 (3.8)	26.0, 26.2
71.	SOG (two storey)	20.5	27.0	35.5	26.9 (2.3)	26.8, 26.9	18.5	25.5	36.5	25.8 (3.0)	25.7, 25.9
72.	SOG (two storey)	23.5	27.0	32.0	27.1 (1.6)	27.1, 27.2	19.5	27.0	35.5	26.5 (2.7)	26.4, 26.6
73.	Queenslander (single storey)	19.8	27.1	37.5	27.4 (3.1)	27.3, 27.5	17.4	25.6	36.9	26.1 (4.2)	25.9, 26.2
74.	SOG (two storey)	22.5	26.5	31.0	26.4 (1.3)	26.4, 26.5	18.5	26.5	36.5	27.1 (3.9)	27.0, 27.2
75.	SOG (single storey)	20.0	28.0	35.5	28.0 (2.5)	27.9, 28.1	19.0	26.5	36.5	27.01 (3.3)	26.9, 27.1
76.	Queenslander (single storey)	16.5	25.5	35.5	24.9 (4.4)	24.8, 25.1	16.5	25.5	36.5	25.4 (4.3)	25.2, 25.5
77.	SOG (single storey)	19.5	25.5	32.5	25.5 (2.2)	25.3, 25.6	18.0	26.5	36.5	26.7 (3.8)	26.5, 26.8

Fig. A.1. Photos of Queenslander houses.

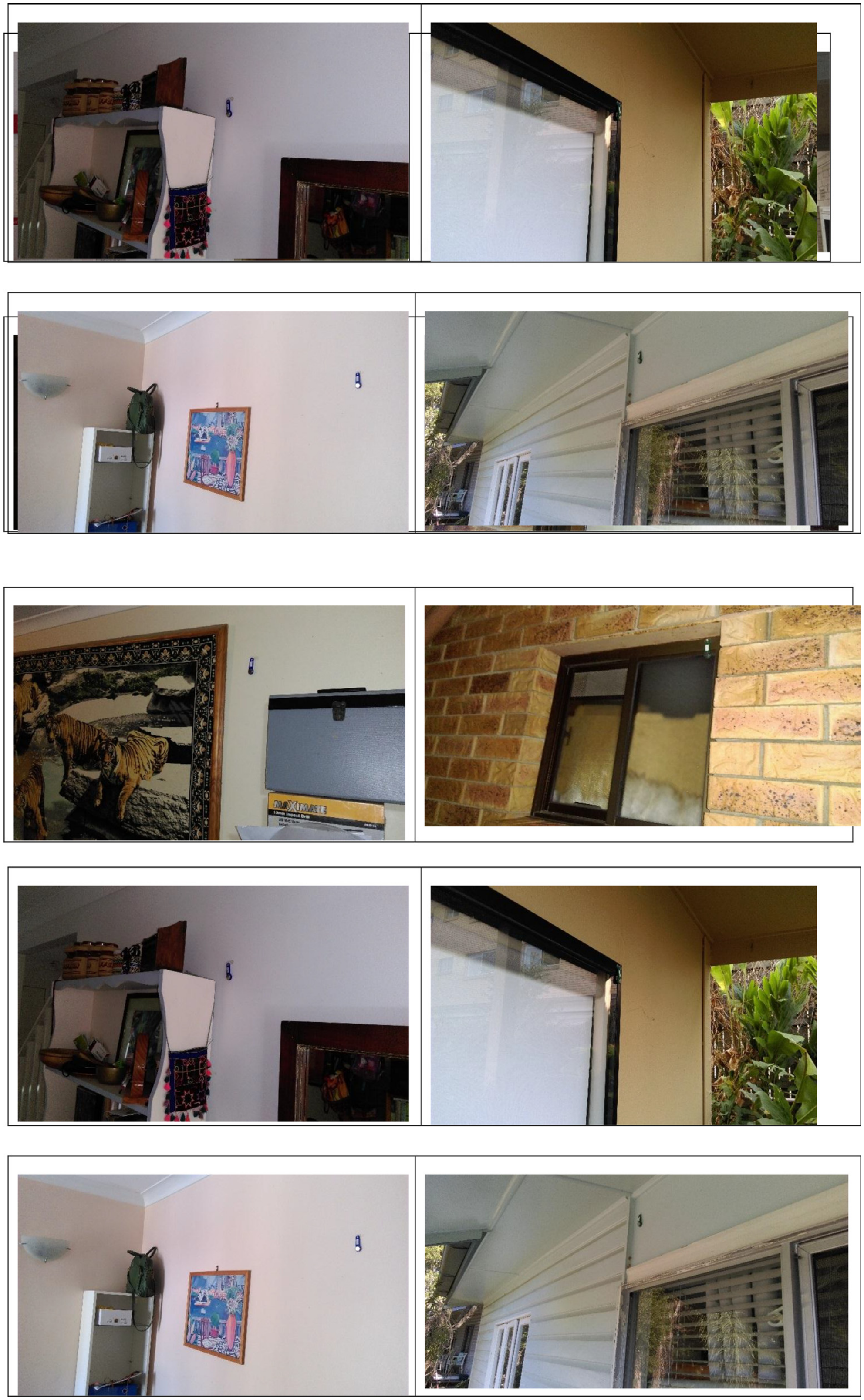

Fig. A.2. Photos of temperature sensors installed both indoor and outside of five of the houses.

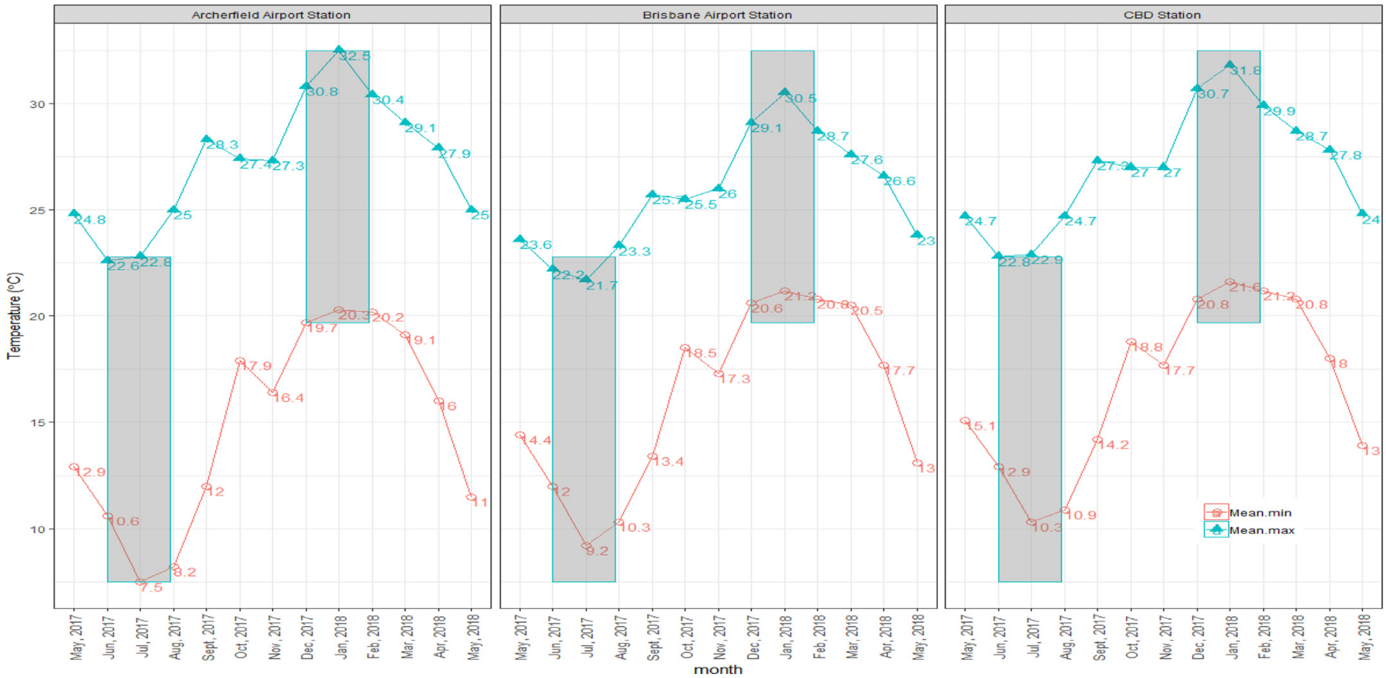

Fig. A.3. Monthly mean outdoor temperatures from three BOM stations in Brisbane. Each panel represents one station.

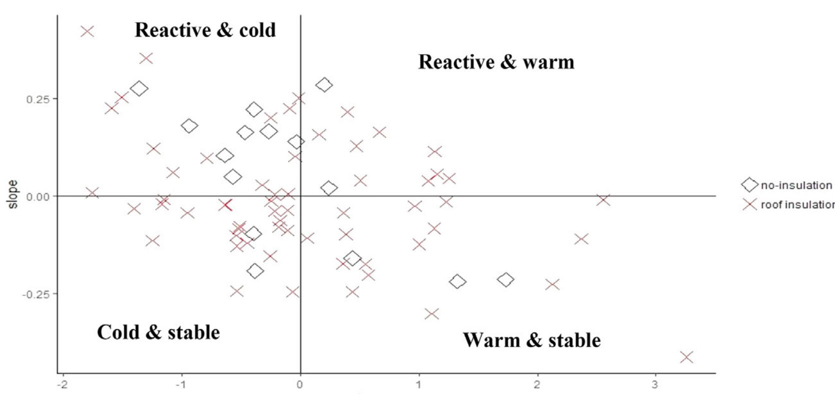

Fig. A.4. Scatter plot of differences from the mean slope (0.42) and intercept (20 °C) of the regression model (cool season). Houses with a higher than mean intercept are warmer than average. Houses with a higher than mean slope have a stronger association with the outdoor temperature. The plot shows the influence of roof insulation.

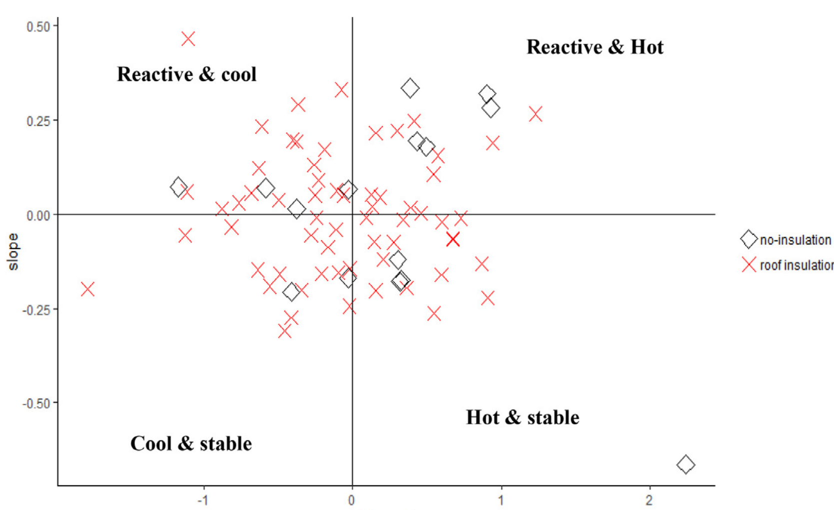

Fig. A.5. Scatter plot of differences from the mean slope (0.41) and intercept (26.2 °C) of the regression model (warm season). Houses with a higher than mean intercept are warmer than mean. Houses with a higher than mean slope have a stronger association with the outdoor temperature. The plot shows the influence of roof insulation.

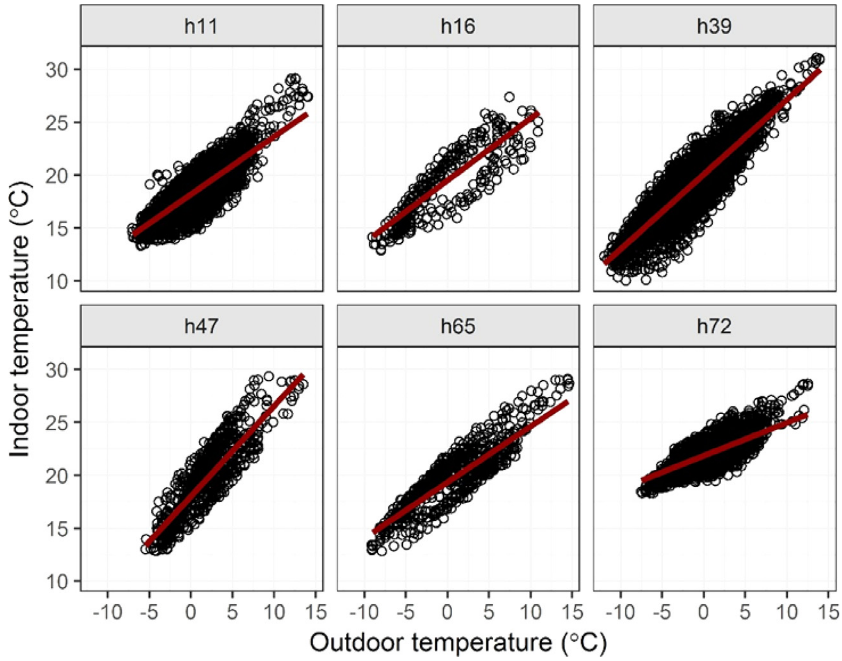

Fig. A.6. Scatter plot of indoor and outdoor temperature with the fitted regression line in six randomly selected houses during the cool season.

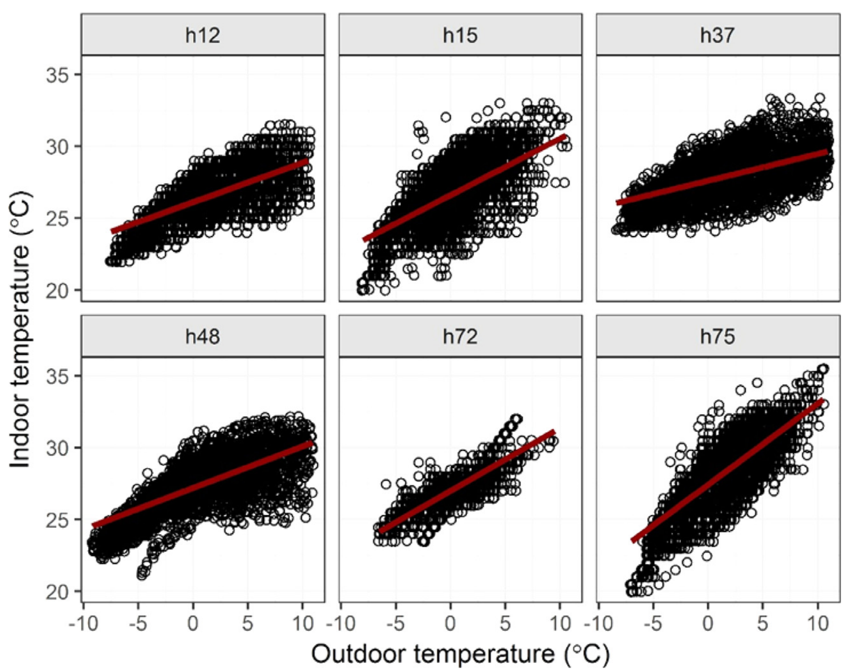

Fig. A.7. Scatter plot of indoor and outdoor temperature with the fitted regression line in six randomly selected houses during the warm season.

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